Physics Capabilities of a Large Liq-Ar Atmospheric detector

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(work with V. Barger, P. Ghoshal, S. Goswami, D. Marfatia, S. Prakash, S. Raut, and S Uma Sankar)

arXiv 1203.6012

PXPS Meeting, Fermilab, June 18, 2012

Atmospheric detectors... Some strengths and limitations

Atmospheric detectors collect neutrino fluxes which are uncertain by 10 - 20% in absolute value (Flavour ratios less uncertain)

Fluxes are sharply dropping functions of energy,

$$\frac{d\phi_\nu}{dE} \sim E^{-\gamma} \text{ and } \gamma \simeq 3 \text{ for } \nu_\mu \text{ and } \simeq 3.5 \text{ for } \nu_e$$

At energies where flux is significant (below ~ 2 GeV), neutrino-nucleon cross-section has significant uncertainties

Also, at energies where flux is significant (below ~ 2 GeV), produced charged lepton may have significantly different direction from incoming neutrino

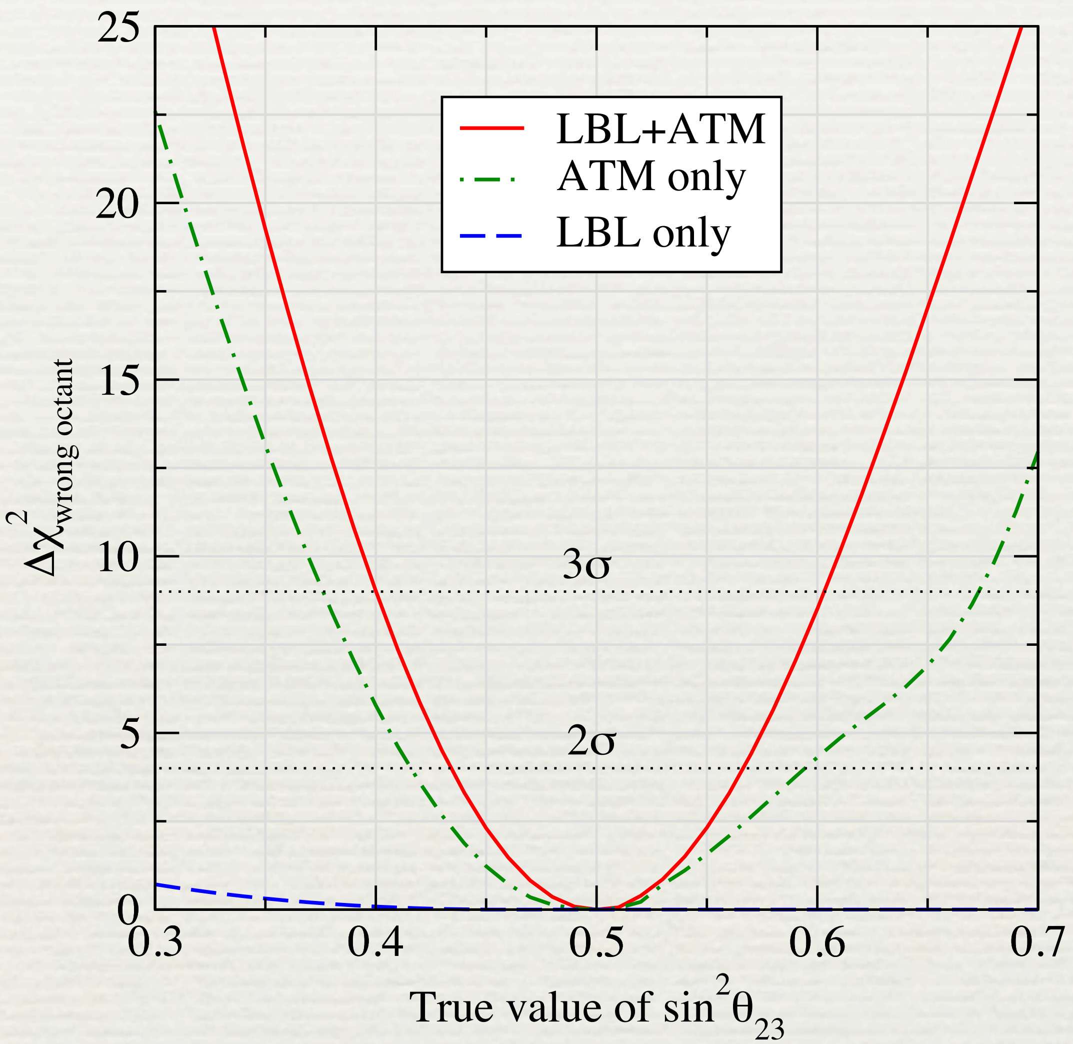
Atmospheric detectors... Some strengths and limitations

Thus there is an inherent lack of precision in L and in E on an event-by-event basis in atmospheric detectors, which translates into uncertainties in measurements of Δm^2 and $sin^2 2\theta_{23}$

Unlike LBL experiments, atmospheric detectors , however, tap into a very broad band in L (20 km to 12500 km) and E (100 MeV to 10 TeV).

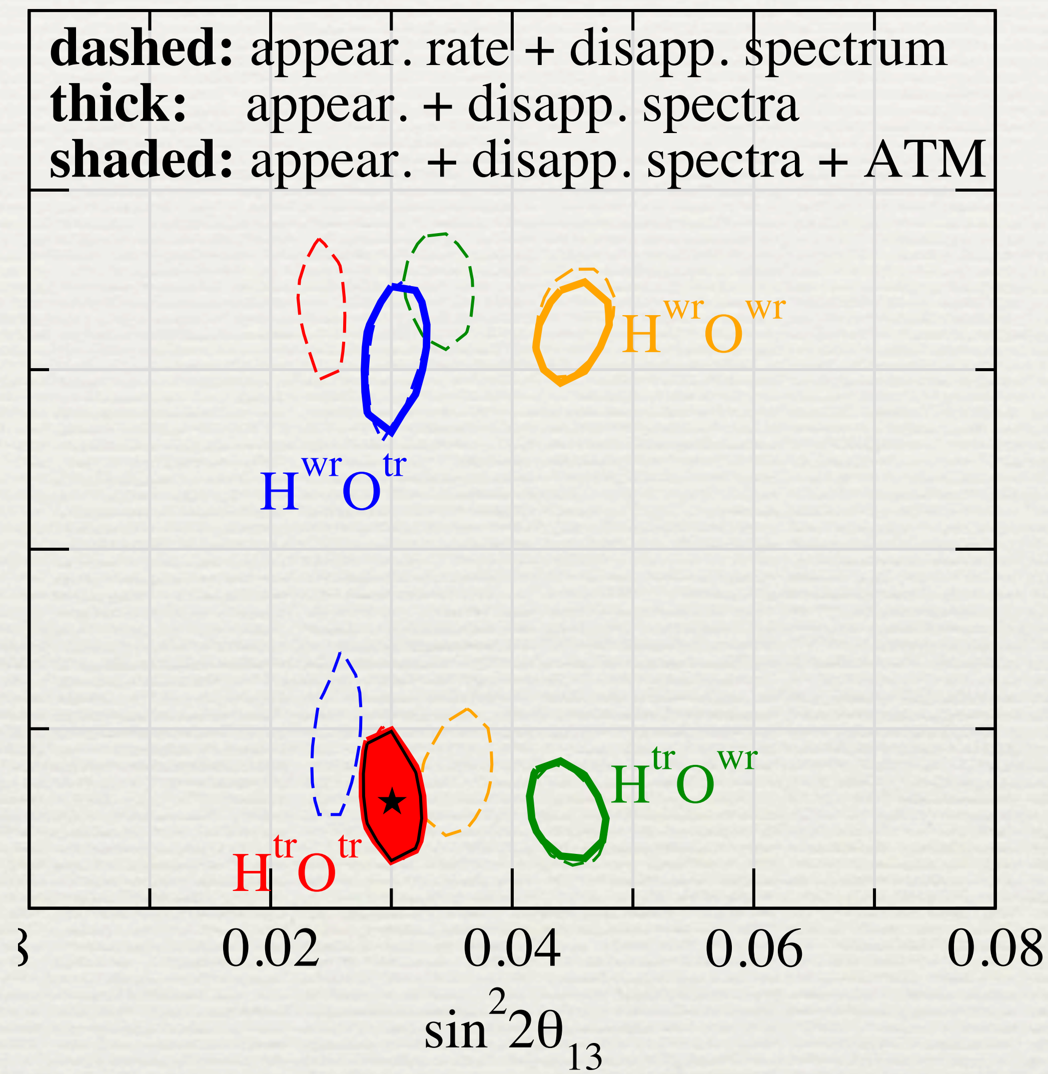
Allows resolution of parameter degeneracies which are a feature of LBL set-ups.

Earlier studies have shown the power of combining LBL + ATM data to maximize the physics output.........



Huber, Maltoni and Schwetz
hep-ph 0501037

T2K-II + HK, 295 km

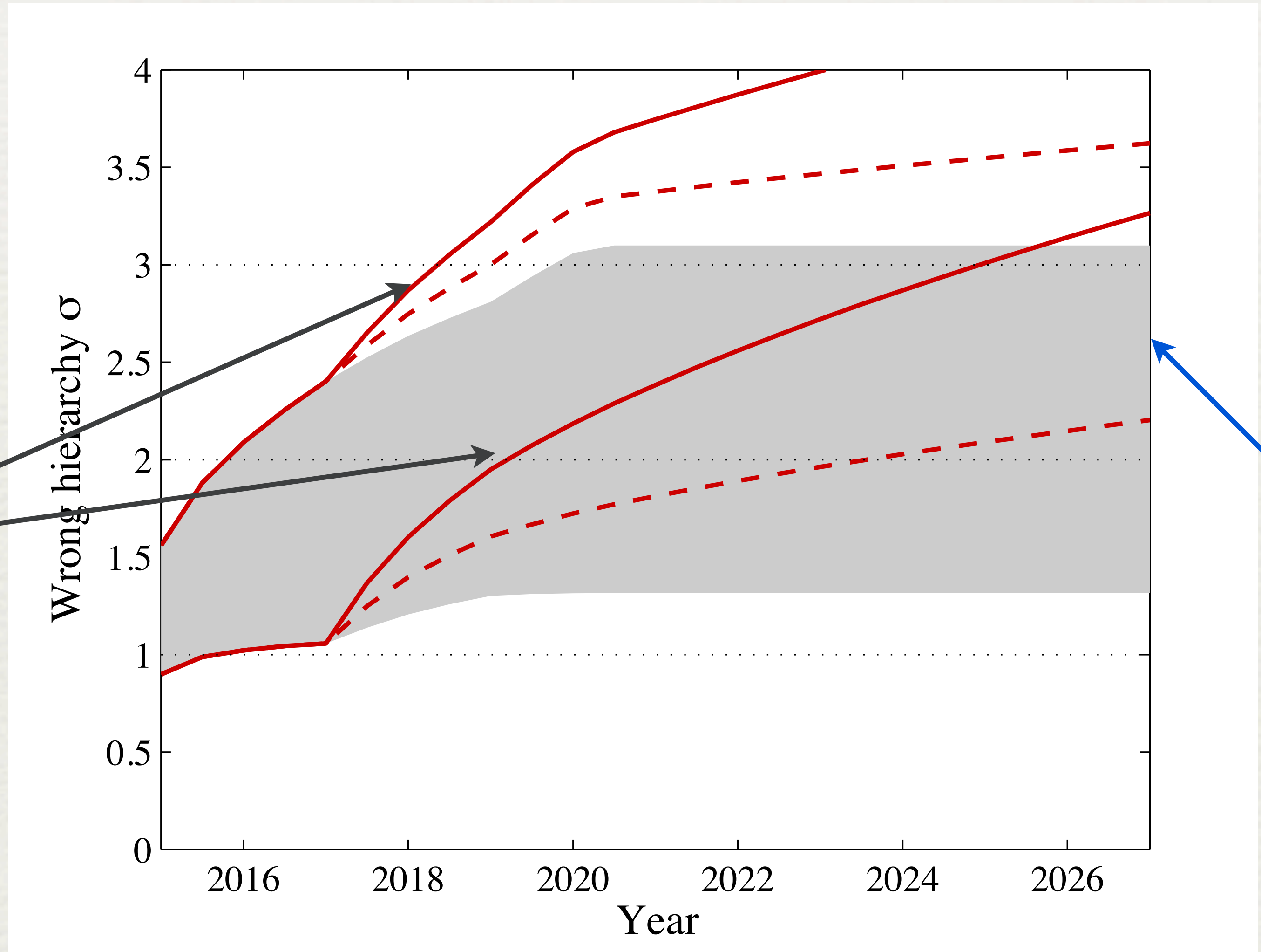


Campagne, Maltoni, Mezetto and Schwetz
hep-ph 0603172

SPS + MEMPHYS, 130 km

Earlier studies have shown the power of combining LBL + ATM data to maximize the physics output...........

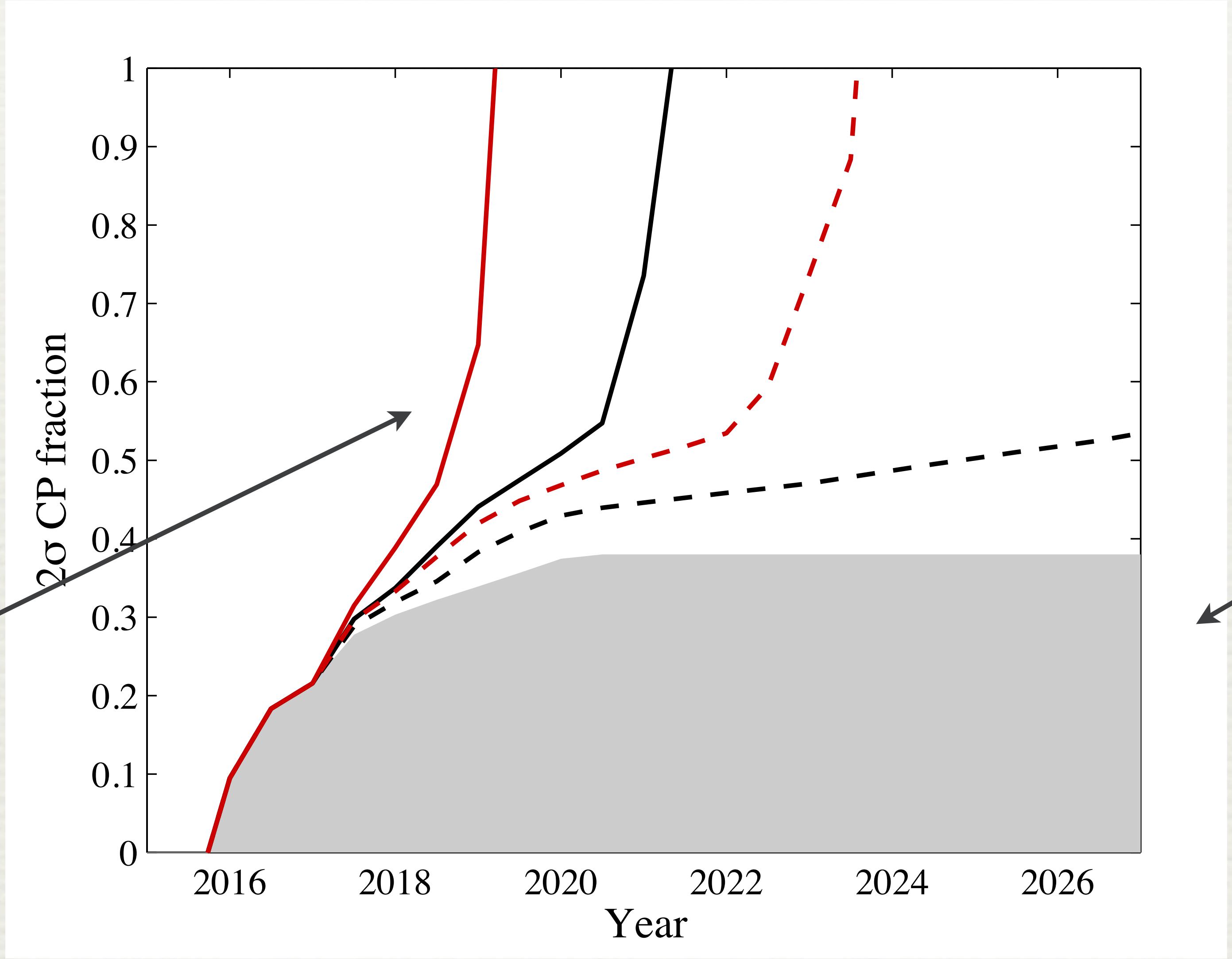
INO +T2K + NOva



T2K + NOva

Blennow and Schwetz
arXiv 1203.3388

INO + T2K + NOvA, hierarchy sensitivity, Earlier studies have shown the power of combining LBL + ATM data to maximize the physics output...........



T2K + NOva

INO

Large θ_{13} ....Some consequences

Recent result from Daya Bay $\sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)$

Recent result from RENO $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$

Measurements significantly impact the planning of future neutrino facilities.

Large θ_{13} ....Consequences for Atmospheric Detectors

Importance of future large mass atmospheric detectors has increased, e.g INO and the case for a Liq Ar detector, because large θ_{13} allows them to tap into matter effects better, and provides a shot at determining the mass hierarchy and octant of θ_{23}

The case for combining super-beam facilities with large mass atmospheric detectors analytically and both analytically and physically (LBNE with large Liq Ar) has become stronger.

Large θ_{13} ....Some consequences

$$P_{\alpha\beta} = P^{(0)}_{\alpha\beta} + \alpha\, P^{(1)}_{\alpha\beta} + \mathcal{O}(\alpha^2)$$

$$P^{(0)}_{e\mu} = s^2_{23}\,\frac{\sin^2 2\theta_{13}}{C^2_{13}}\,\sin^2 C_{13}\Delta\,,$$

$$C_{13} \equiv \sqrt{\sin^2 2\theta_{13} + (A - \cos 2\theta_{13})^2}\,.$$

$$P^{(1)}_{e\mu} = -2s^2_{12}\,s^2_{23}\,\frac{\sin^2 2\theta_{13}}{C^2_{13}}\,\sin C_{13}\Delta$$

$$\times\left[\Delta\,\frac{\cos C_{13}\Delta}{C_{13}}(1 - A\cos 2\theta_{13}) - A\,\frac{\sin C_{13}\Delta}{C_{13}}\,\frac{\cos 2\theta_{13} - A}{C_{13}}\right]$$

$$+\, s_{13}\,\sin 2\theta_{12}\sin 2\theta_{23}\,\frac{\sin C_{13}\Delta}{AC^2_{13}}\Big\{\sin\delta_{\rm CP}\,[\cos C_{13}\Delta - \cos(1+A)\Delta]\,C_{13}$$

$$+\cos\delta_{\rm CP}\,[C_{13}\sin(1+A)\Delta - (1 - A\cos 2\theta_{13})\sin C_{13}\Delta]\Big\}\,,$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}\,,$$

$$A \equiv \frac{2EV}{\Delta m^2_{31}} = \frac{VL}{2\Delta}\,.$$

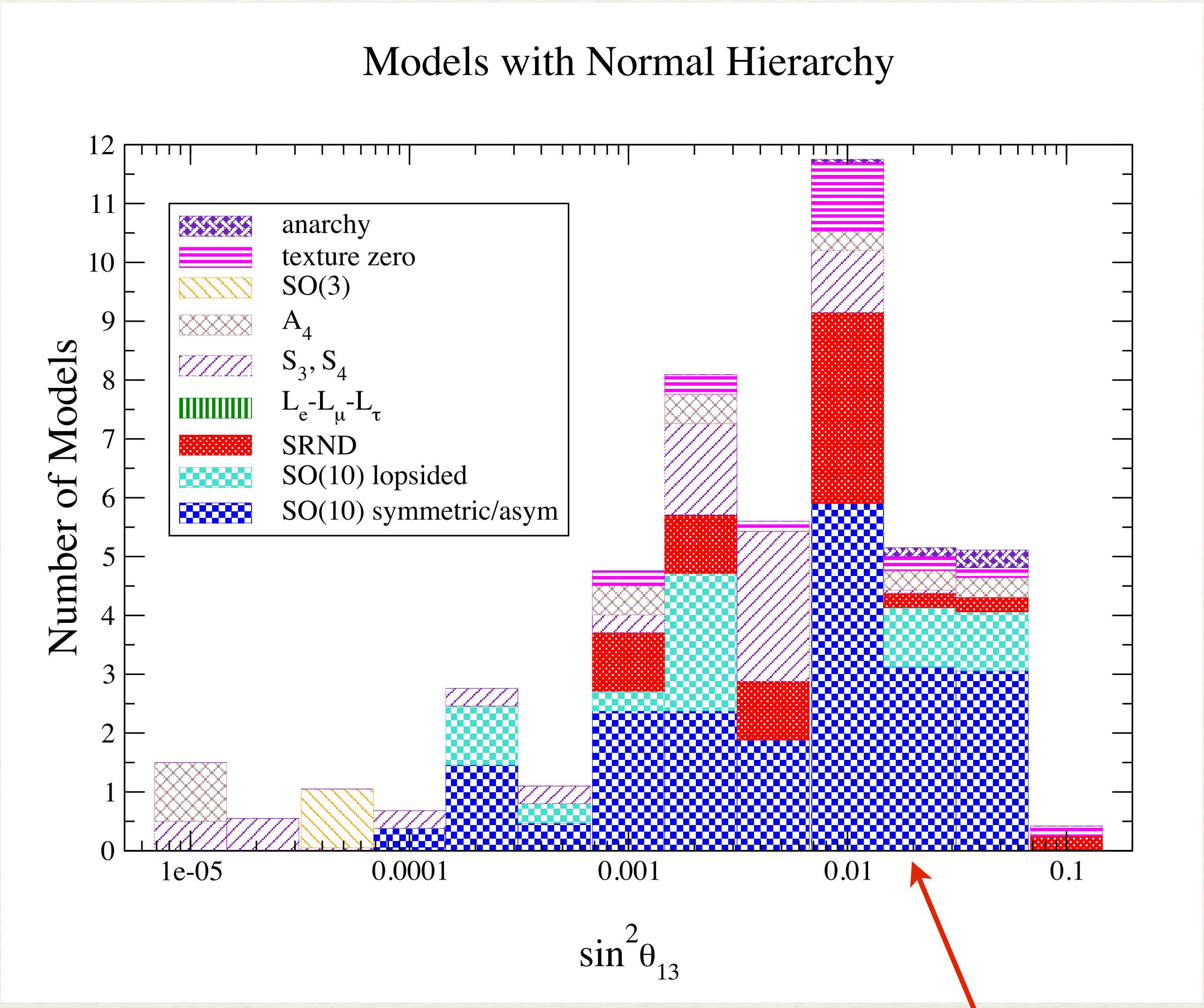
Akhmedov et al,hep-ph 0402.175

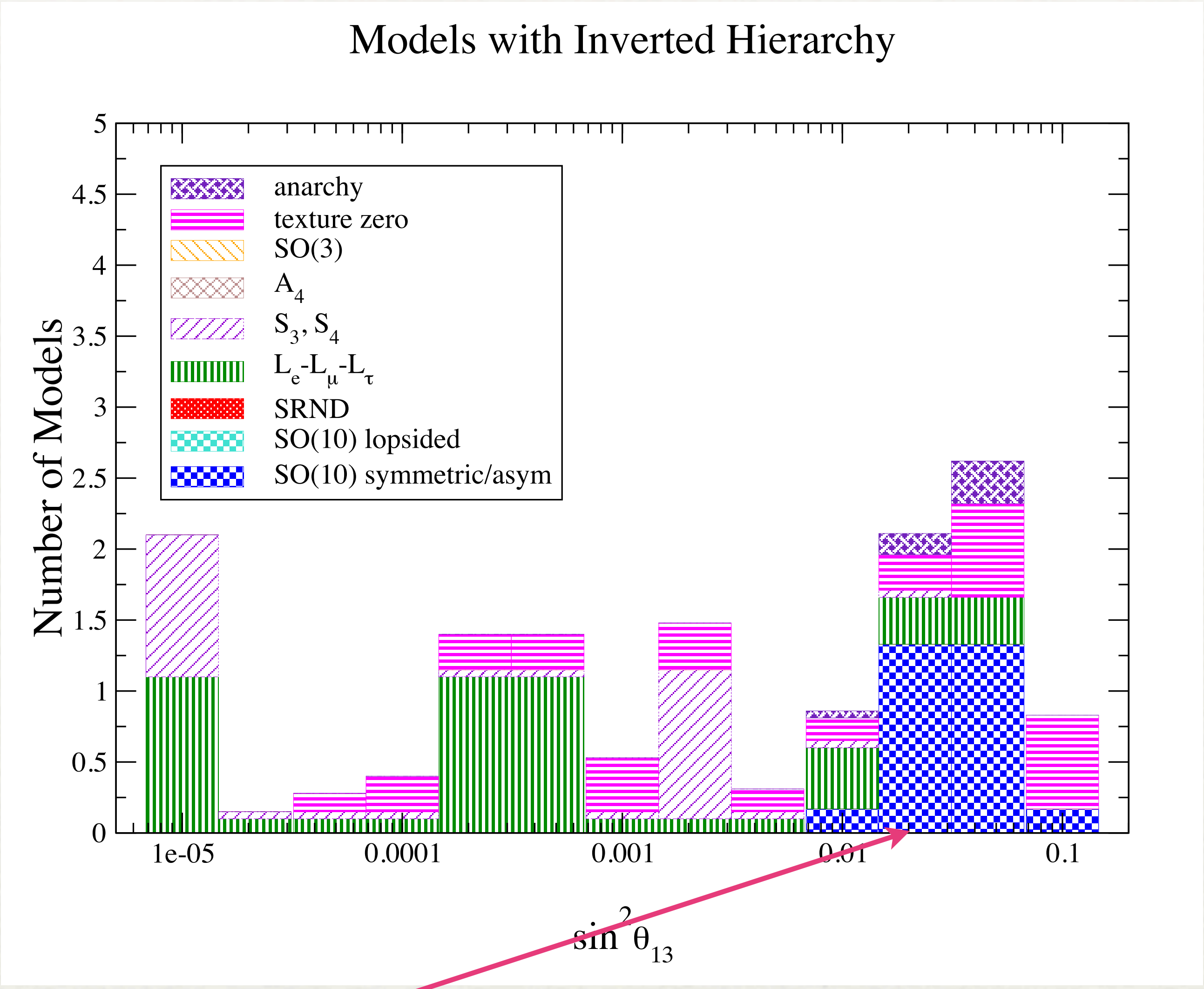
$$A_{CP} = \frac{P_{\nu_e\to\nu_\mu} - P_{\bar\nu_e\to\bar\nu_\mu}}{P_{\nu_e\to\nu_\mu} + P_{\bar\nu_e\to\bar\nu_\mu}} \sim \frac{1}{sin\theta_{13}}$$

Large θ_{13} does not automatically mean enhanced CP measurement.

Overall CP sensitivity depends on baseline and type of expt

Importance of the mass hierarchy........



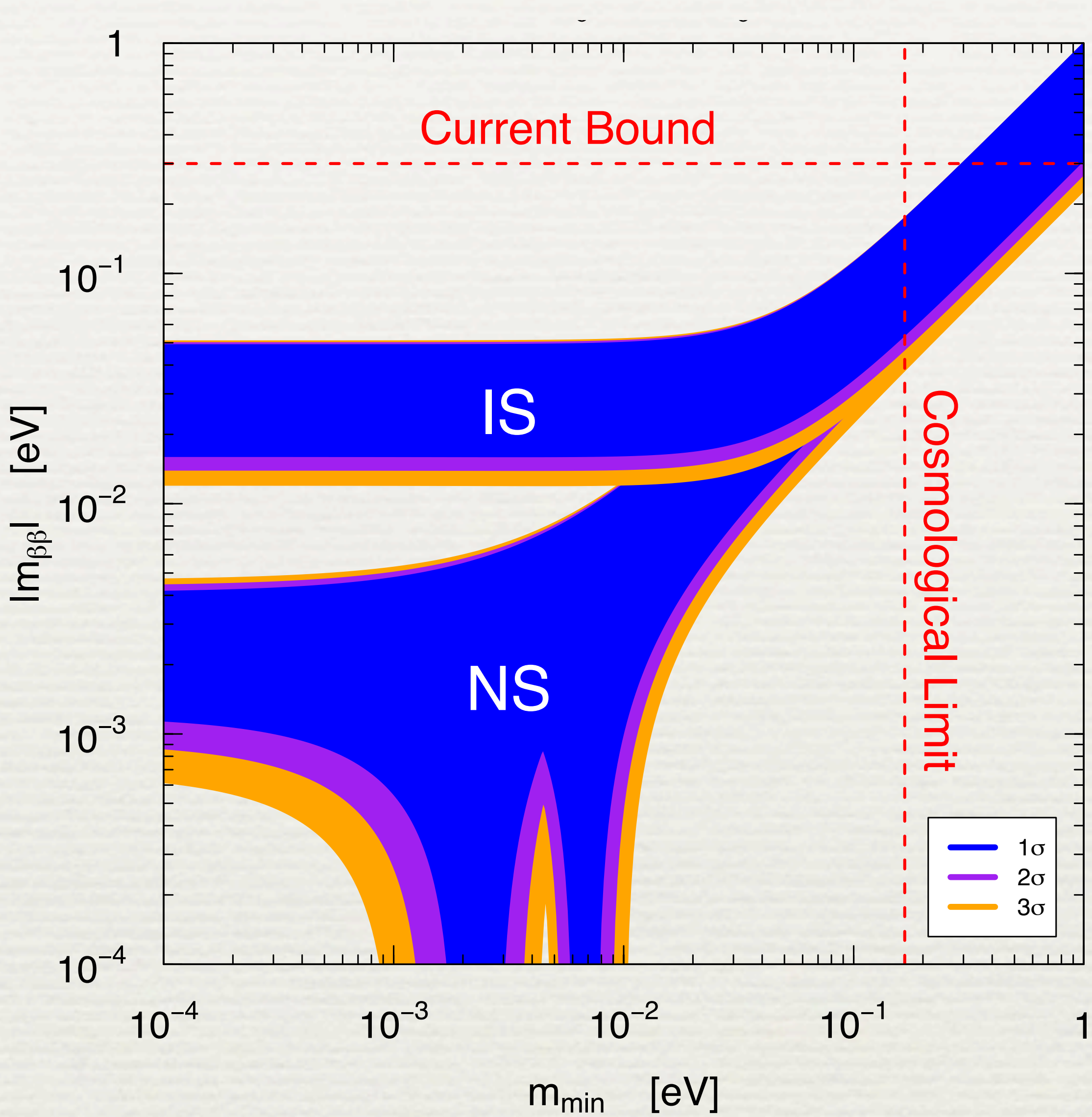


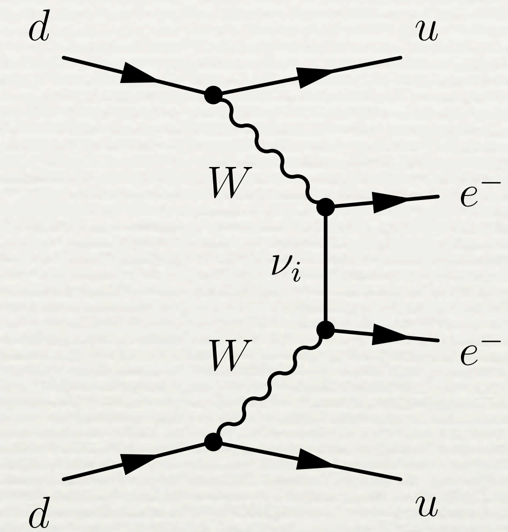
Albright and Chen, hep-ph 0608137

sin^2 2th_13= 0.1

A very useful discriminator of BSM models........

Importance of the mass hierarchy........



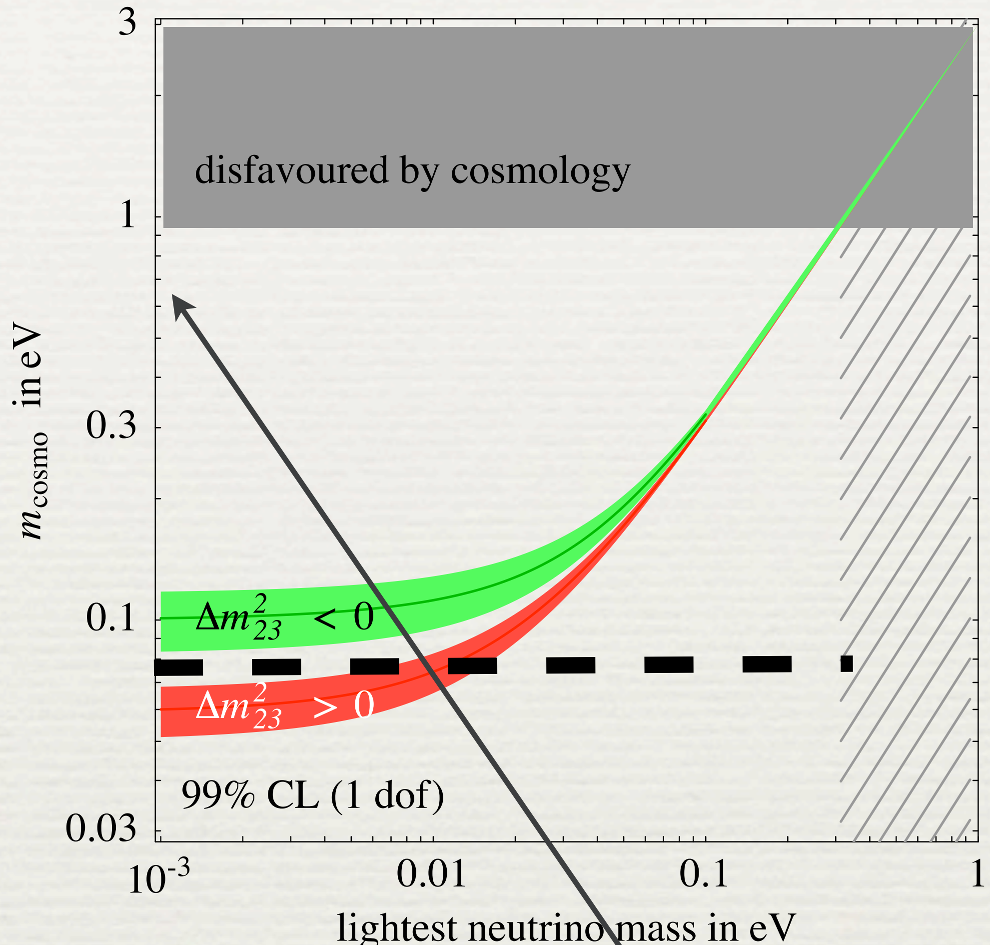


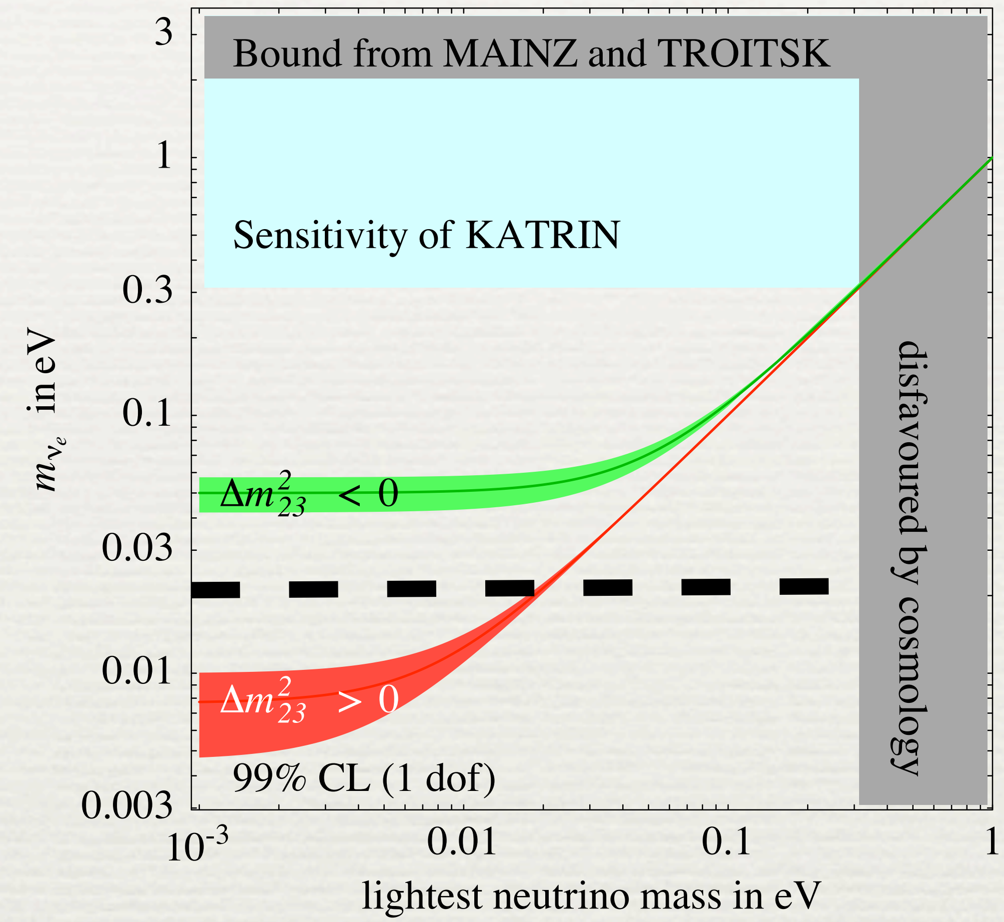
Bilenky and Giunti, 1203.5250

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i .$$

Width of $0\nu\beta\beta$-decay depends on $|m_{\beta\beta}|^2$, the effective majorana mass squared.

Importance of the mass hierarchy........





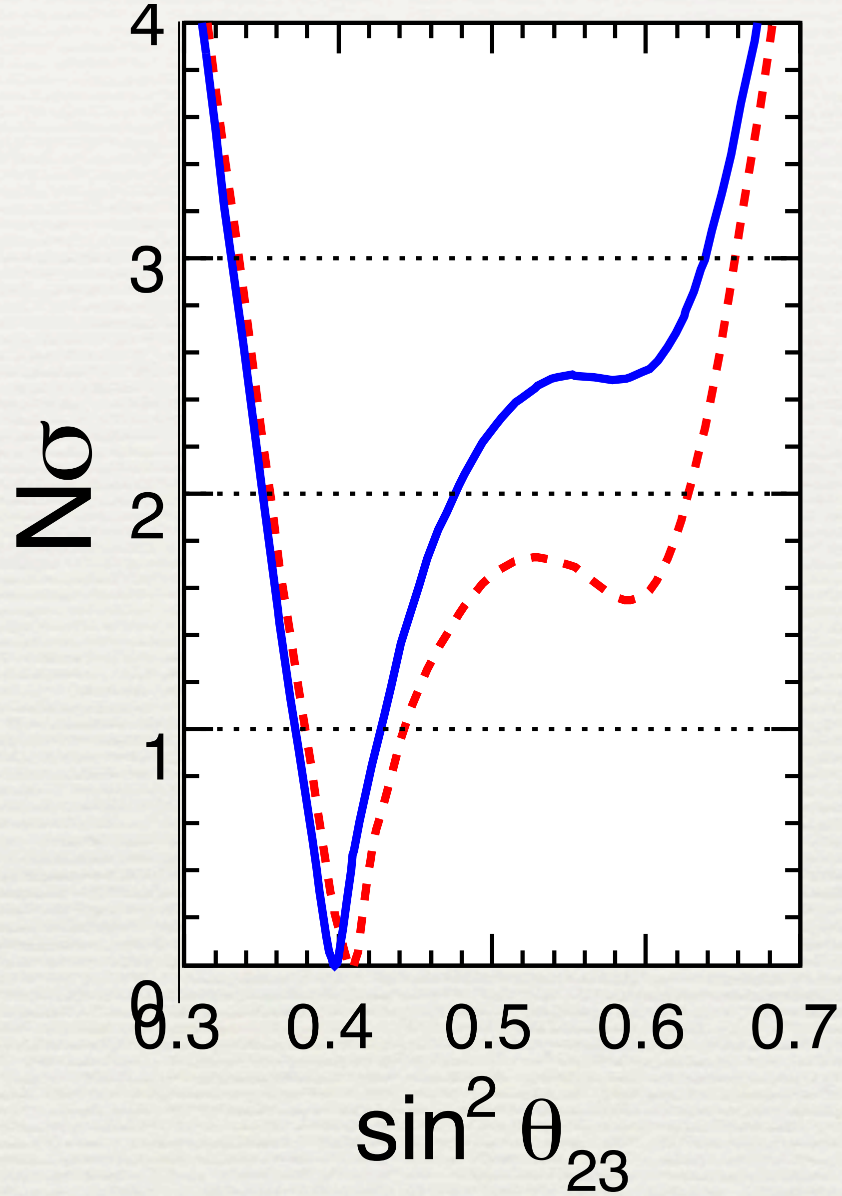
WMAP/SDSS/Hubble current bound
(conservative)
R. De Putter et al, 1201.1909, M Moresco et al,
1201.6658

Strumia and Vissani, hep-ph 0503246
Parke, FNAL CONF 06-248-T

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}\,.$$

The link between hierarchy and sensitivity requirements of experiments.........

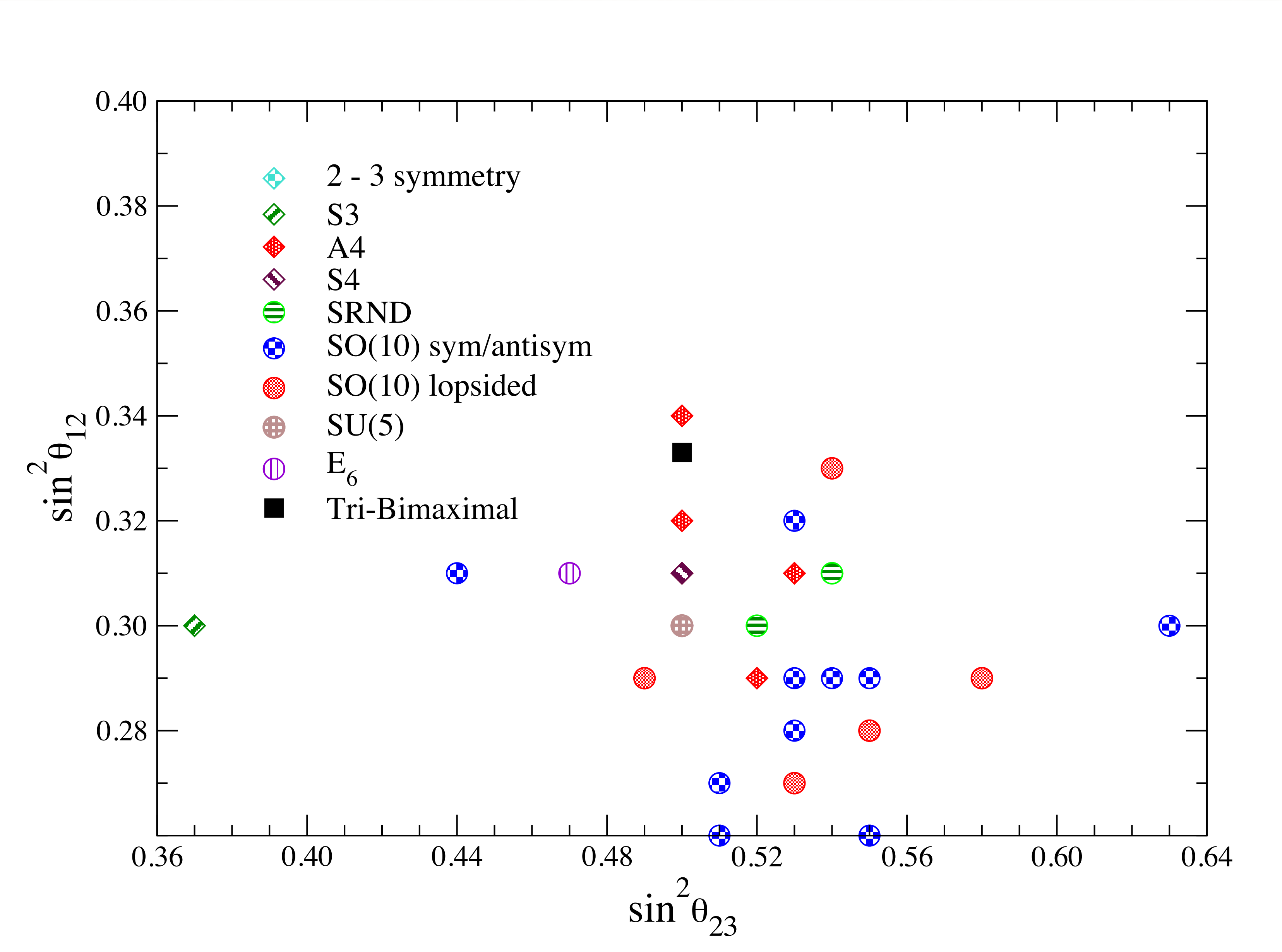
Octant of θ_{23} ....



Fogli et al, arXiv 1205.5254

Present Global data exhibits ~ 2 sigma preference for first octant, indicating a significant deviation from maximal mixing.

Octant of θ_{23}...........



Albright, arXiv 0905.0146

Discrimination among models using the value of θ_{23}

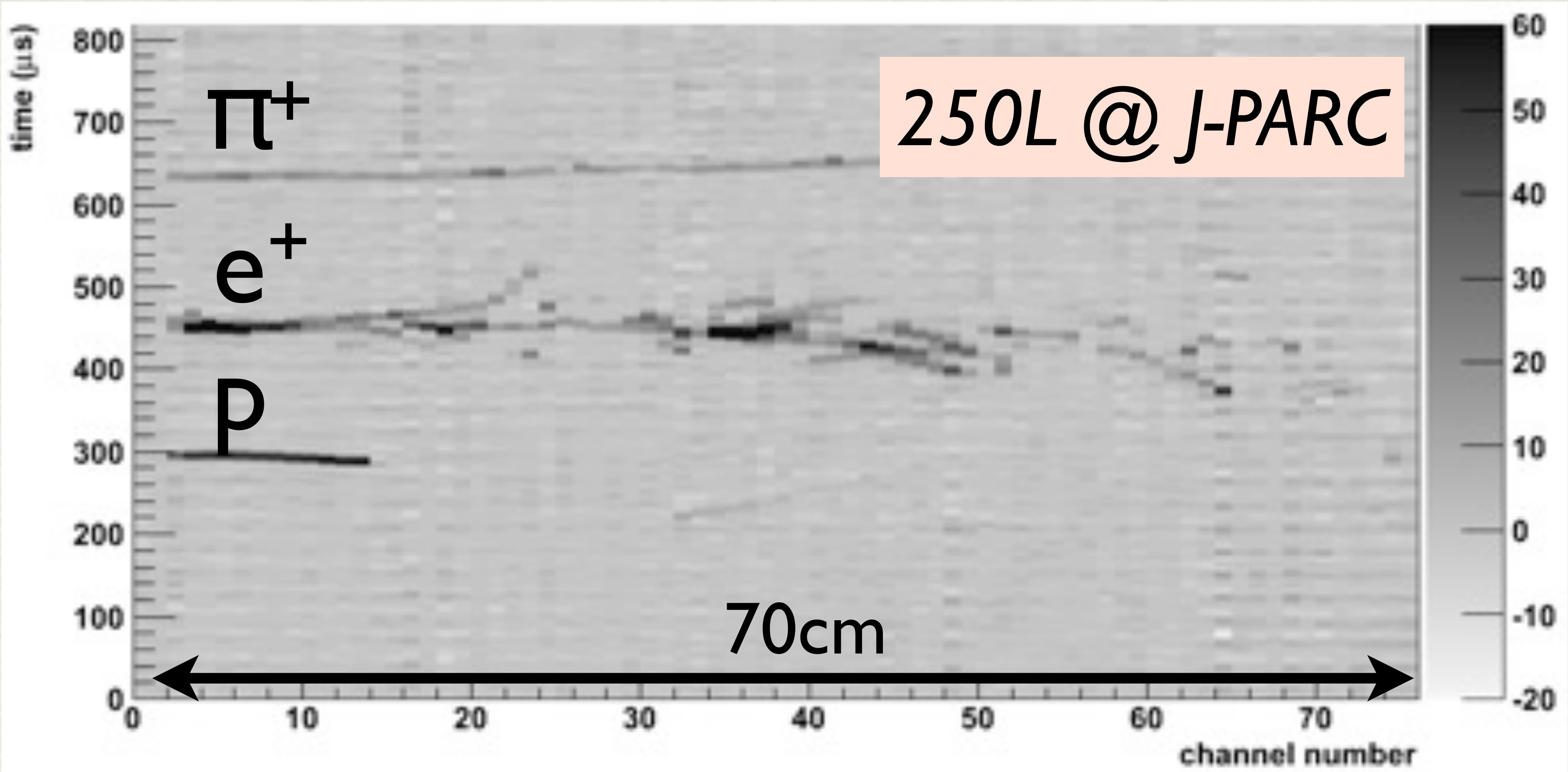
Liquid Argon Detectors........

A Rubbia

Particle ionization tracks can be drifted over several meters leading to homogeneous and high accuracy imaging over large volumes.

Bubble chamber-like 3D imaging and mm scale spatial resolution.........

Particle id via dE/dx and/or decay product id



Liquid Argon Detectors........magnetization

Studies done for Liq-AR TPC's for neutrino factories have examined the feasibility and advantages of magnetization of such detectors

For long tracks 4 m (e.g muons) a field of 0.1 T can provide >3 sigma charge id in this medium. Thus low threshold possible (800 MeV for muons)

Early showering of electrons makes their charge id difficult, but with 1 T field can achieve id for energies 1-5 GeV with 20% efficiency.

A Rubbia arXiv 0908.1286, A Rubbia et al hep-ph/0106088, A Bueno et al hep-ph/0005007, A Bueno et al hep-ph/0010308..........

Liquid Argon Detectors........ Future

R Svoboda, Neutrino 2012 talk

LBNE Reconfiguration options.......Phase I

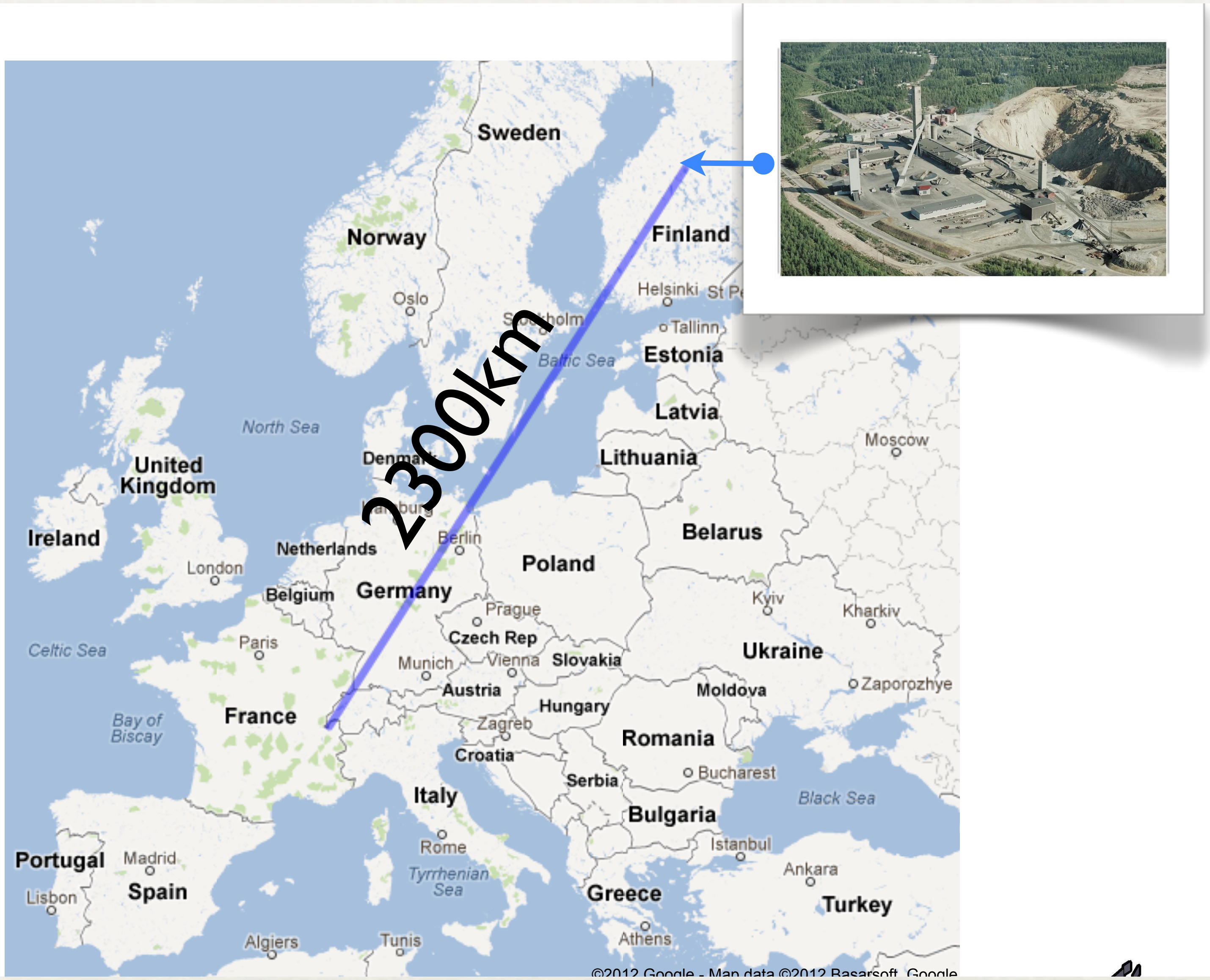
New 700 kW beam line to **Homestake**, no Near Detector, 10 kton Far Detector (would be on surface unless additional funding obtained)

Use existing NuMI beam and build a 15 kton detector underground at the MINOS site in the **Soudan** Mine.

Use existing NuMI beam and build a 30 kton detector on the surface at the NOVA site at **Ash River.**

Decision soon!

Liquid Argon Detectors........ Future



GLACIER

GLACIER/LAGUNA....Pyhasalami, Finland site under serious consideration, 20 kT (initial, w/subsequent increments) underground at 4000 m.w.e, wideband SPSbeam, 2300 km + Atmospheric neutrinos

Liquid Argon Detectors........

A Bueno et al, hep-0701101
A Rubbia

Good calorimetric and angular resolution

$$\begin{aligned}
\sigma_{E_e} &= \sigma_{E_\mu} = 0.01\,, \\
\sigma_{E_{had}} &= \sqrt{(0.15)^2/E_{had} + (0.03)^2}\,, \\
\sigma_{\theta_e} &= 0.03 \text{ radians} = 1.72^\circ, \\
\sigma_{\theta_\mu} &= \sigma_{\theta_{had}} = 0.04 \text{ radians} = 2.29^\circ\,,
\end{aligned}$$

Leads to

$$\sigma_{E_\nu} = \sqrt{(0.01)^2 + (0.15)^2/(yE_\nu) + (0.03)^2}\,,$$

$$\sigma_{\theta_{\nu e}} = 2.8^\circ, \ \sigma_{\theta_{\nu\mu}} = 3.2^\circ$$

with

$$E_{had} = yE_\nu$$

Inputs into calculation..........

Parameter ranges for marginalization..........

- θ_{23} from $38^\circ - 52^\circ$ $(\sin^2\theta_{23} = 0.38 - 0.62)$,
- $|\Delta m^2_{31}|$ from $(2.05 - 2.75) \times 10^{-3}$ eV^2,
- θ_{13} from $5.5^\circ - 11.0^\circ$ $(\sin^2 2\theta_{13} = 0.04 - 0.14)$,
- δ_{CP} from $0 - 2\pi$.

True values......

$(|\Delta m^2_{31}|)_{tr} = 2.4 \times 10^{-3}$

$(\delta_{CP})_{tr} = 0, \ (\sin^2\theta_{23})_{tr} = 0.4, 0.5$ and 0.6

Fixed values......

Δm^2_{21} and θ_{12} are fixed at their best-fit

Errors, Uncertainties and priors..........

Flux normalization error 20%

Flux tilt factor, 5%

Overall cross-section uncertainty 10%

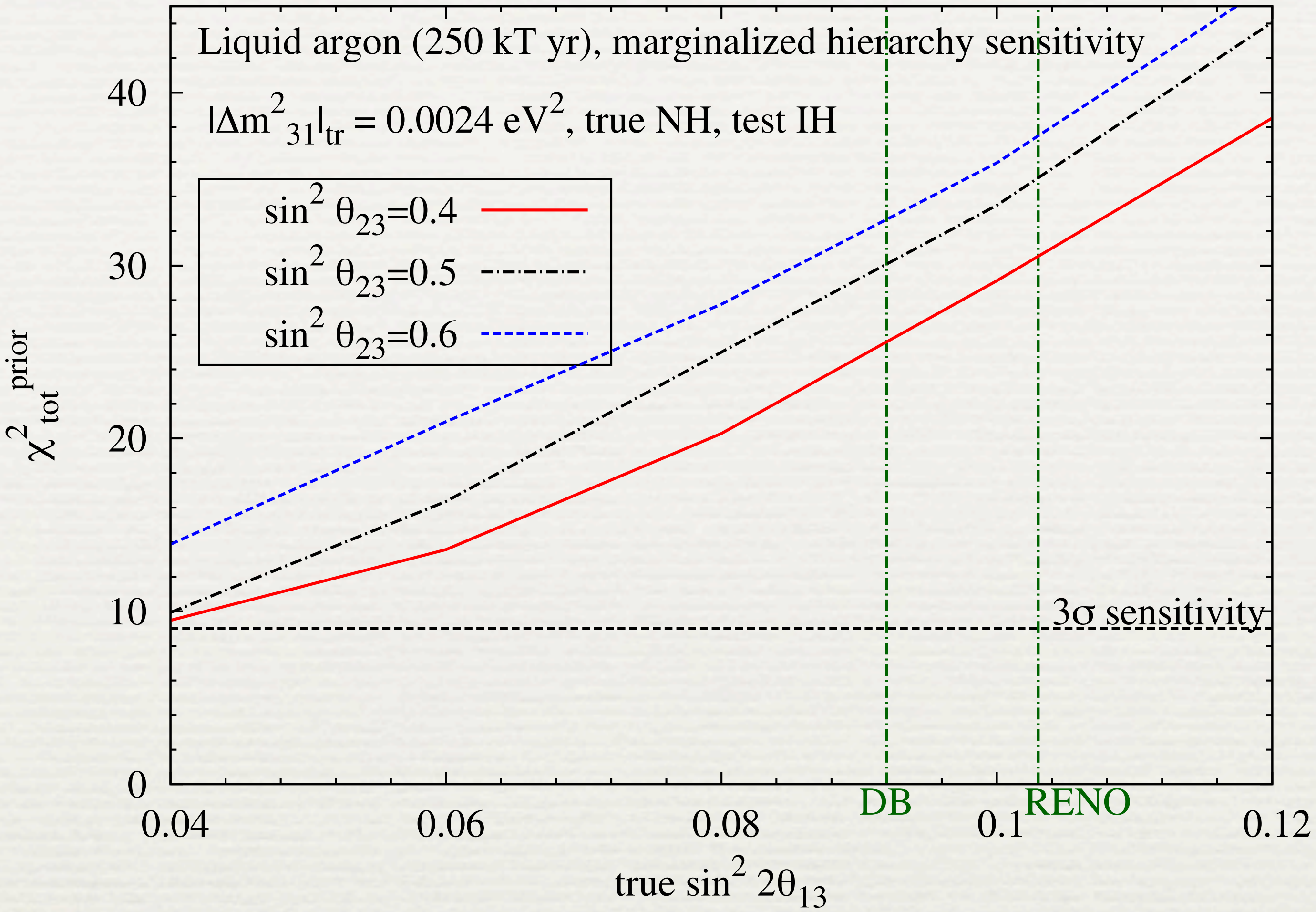
Overall systematic uncertainty 5%

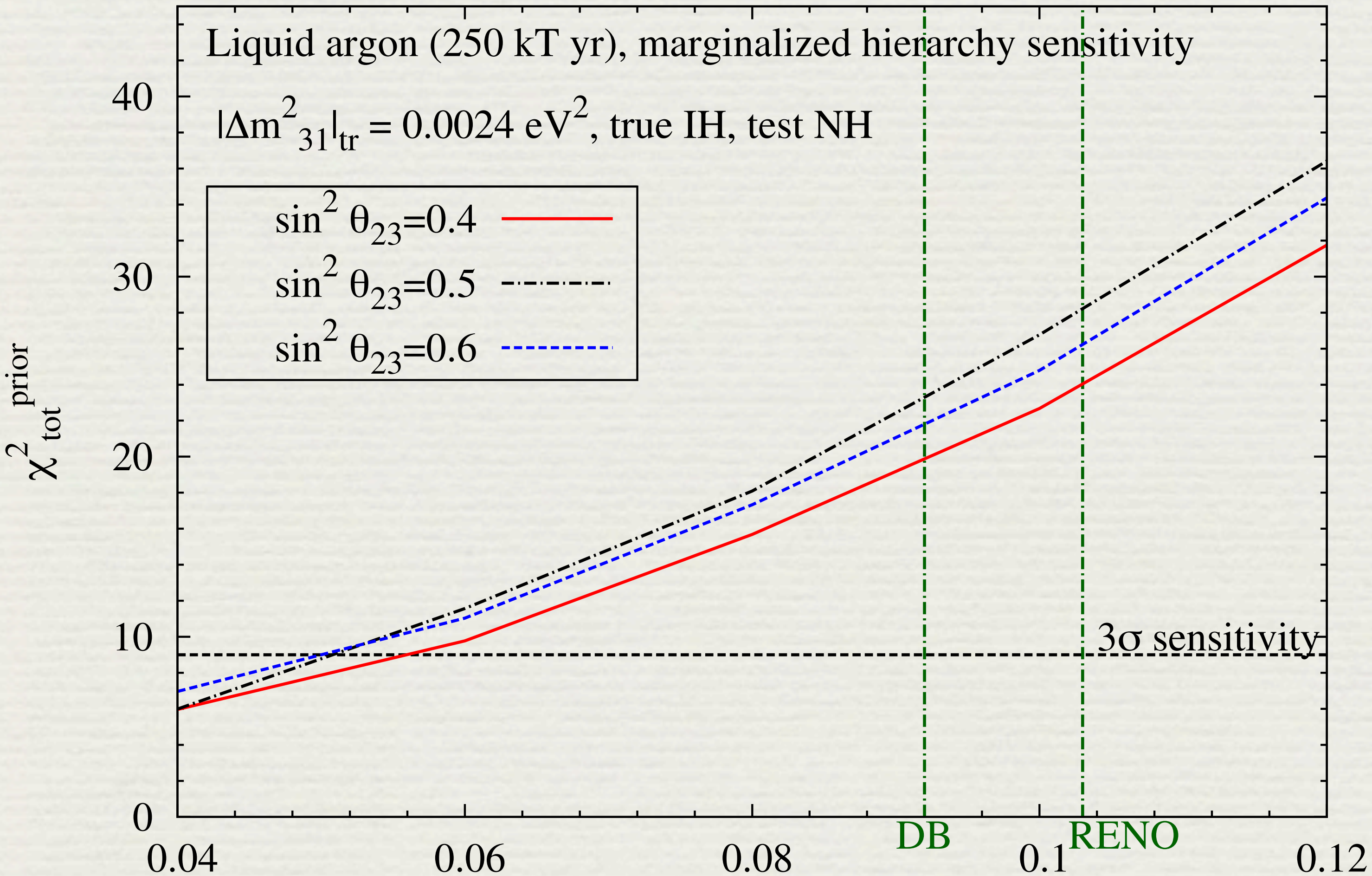
Priors with 1σ ranges: $\sigma(|\Delta m^2_{31}|) = 0.05|\Delta m^2_{31}|$,

$\sigma(\sin^2 2\theta_{13}) = 0.02$, and $\sigma(\sin^2 2\theta_{23}) = 0.02 \sin^2 2\theta_{23}$.

Minimize $\chi^2_\mu + \chi^2_e + \chi^2_{prior}$.

Results..........Hierarchy





Sensitivity strongly depends on matter effects, the detection of which relies on charge id

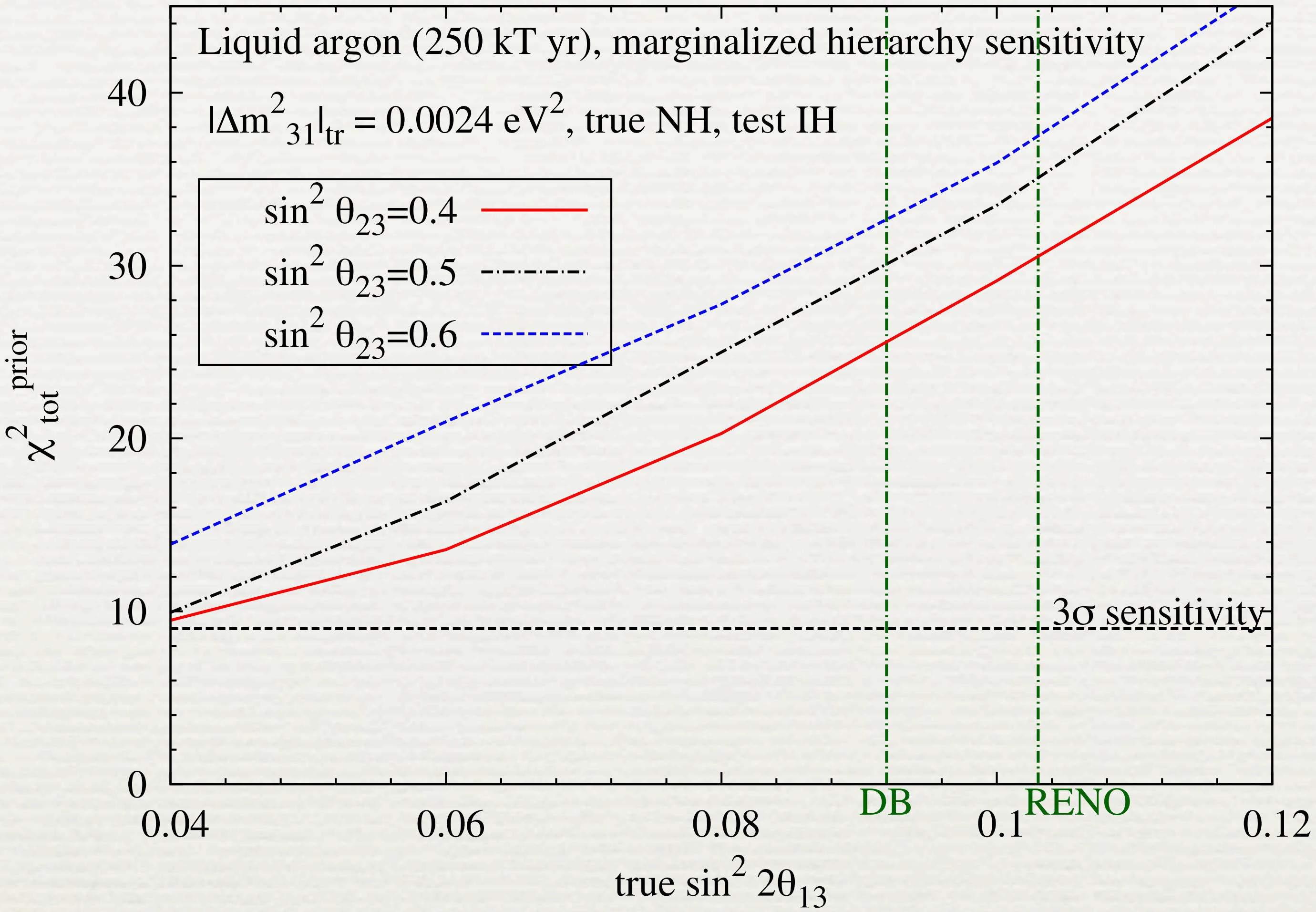
Muons make a larger contribution to sensitivity compared to electrons.

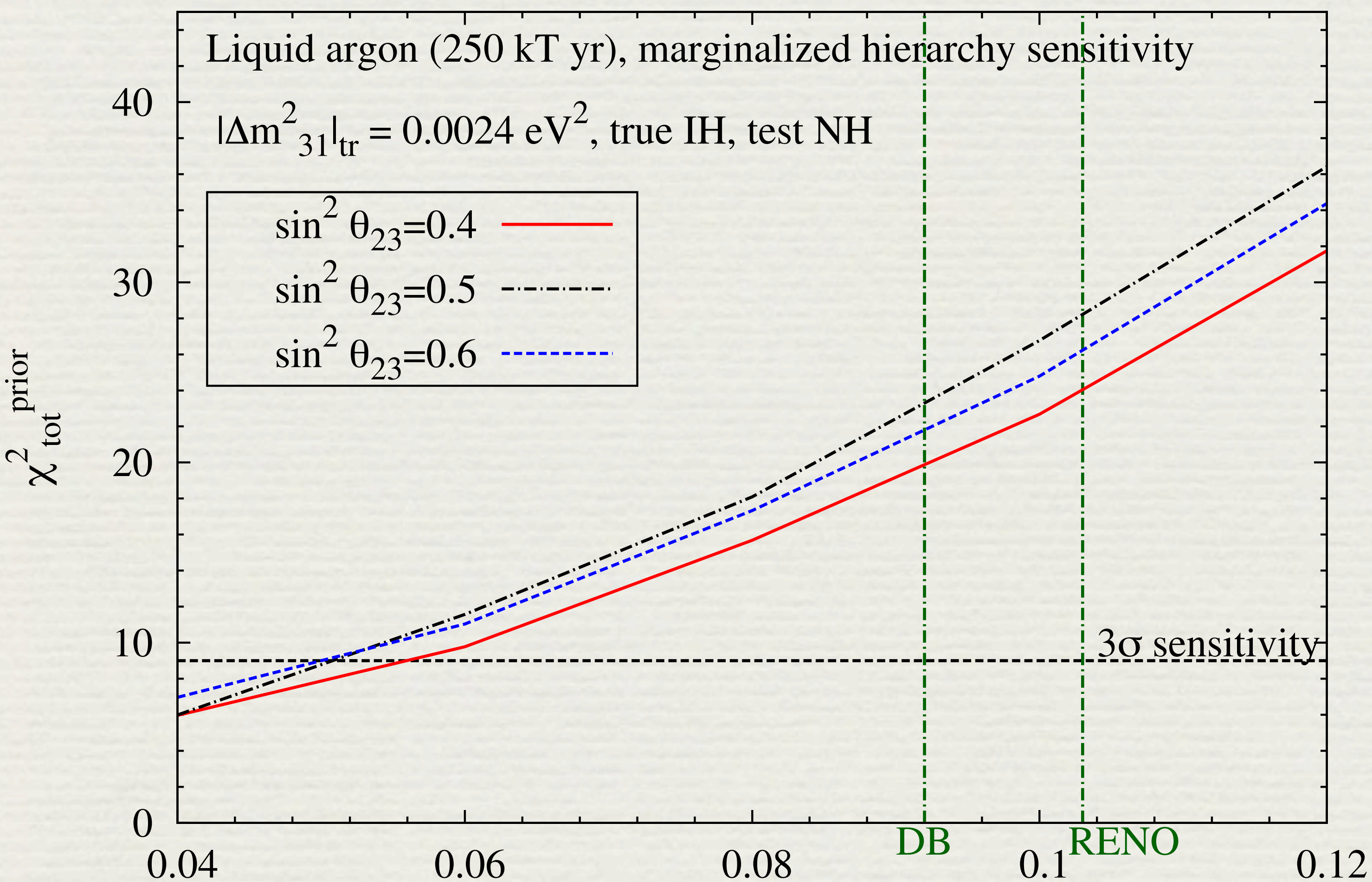
Superior angular resolution of the detector plays an important role

Priors and precision in θ_{13} important.

$\sigma(\sin^2 2\theta_{13})$	χ^2_{NH}	χ^2_{IH}
No Prior	25.6	11.7
0.02	33.5	26.8
0.01	35.8	36.8

Results..........Hierarchy

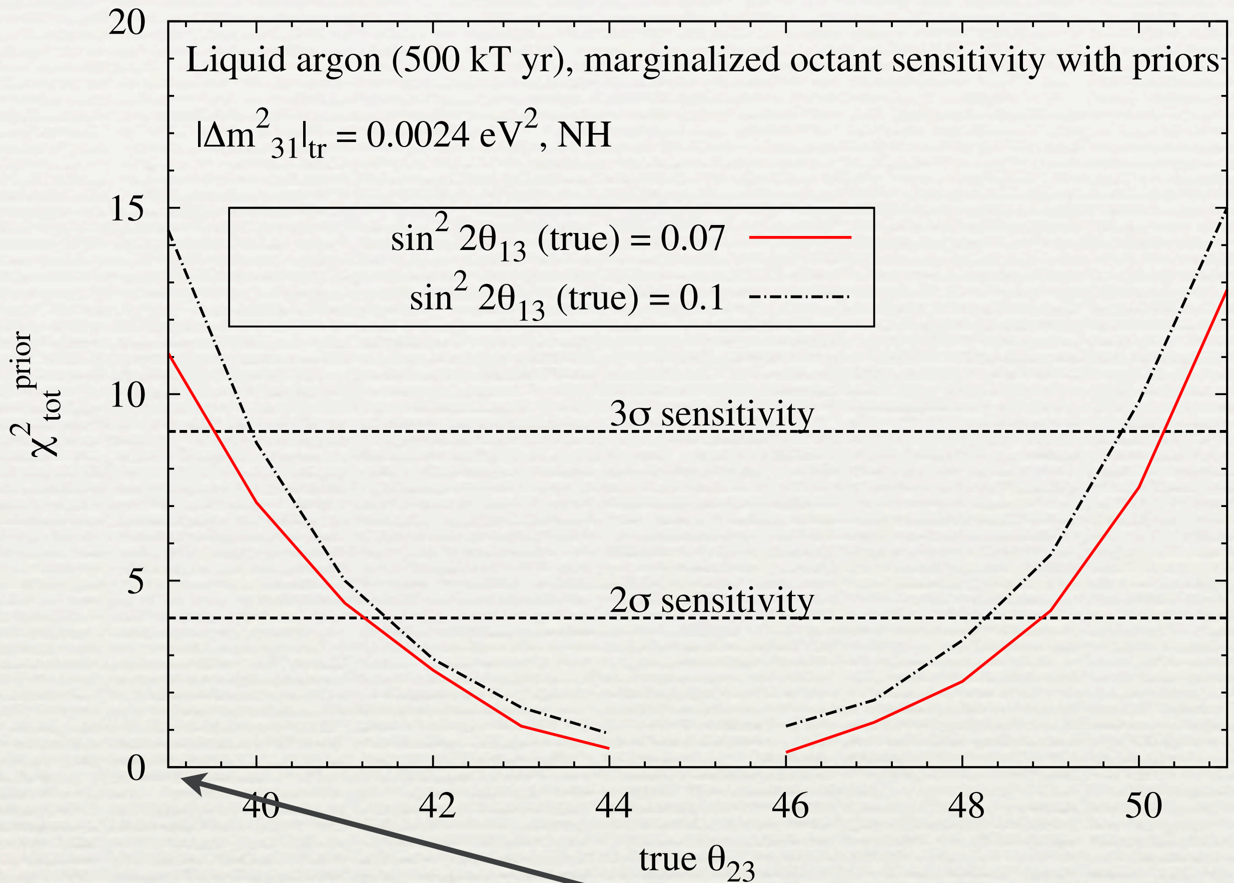


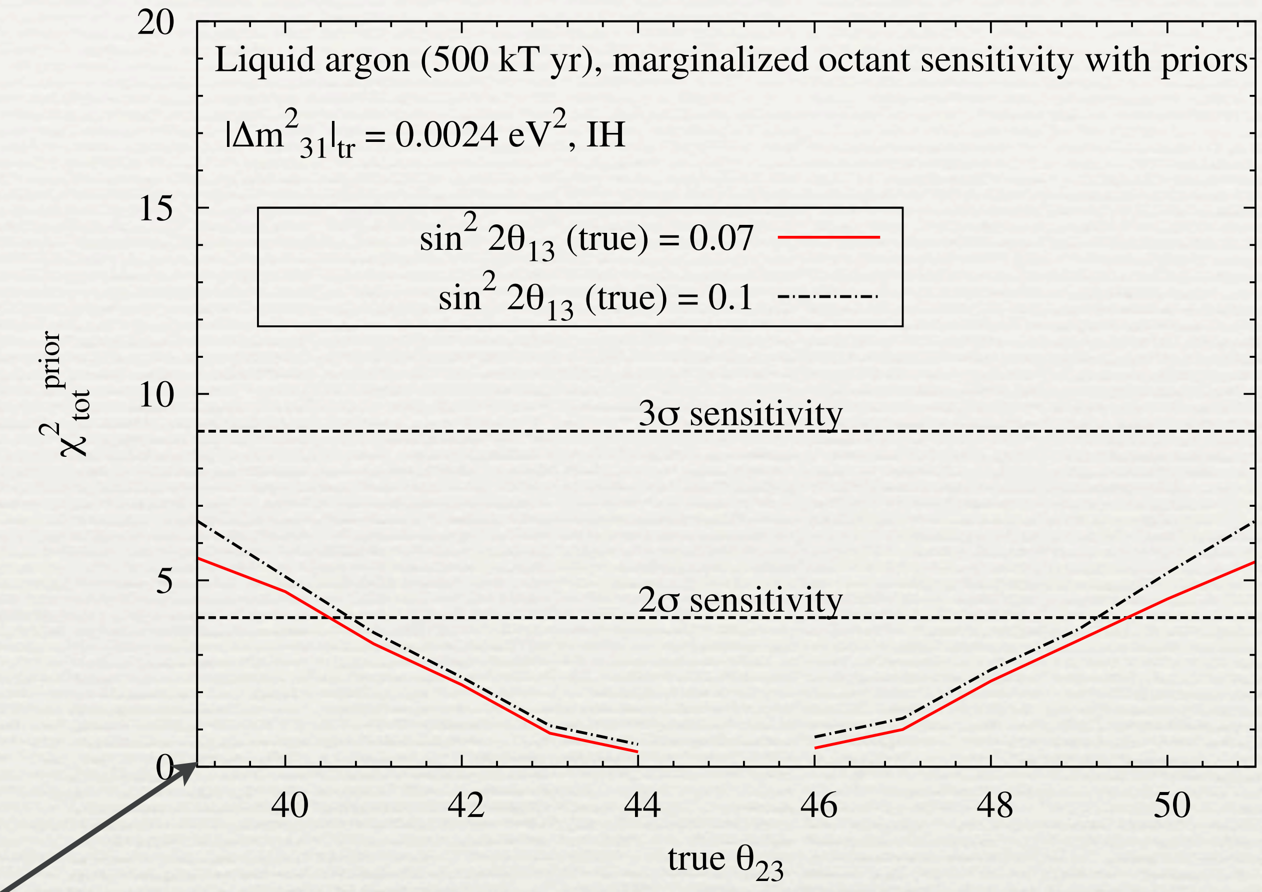


If θ_{13} in 1 sigma range of RENO/DB then 250 kT-yr exposure gives ~5 sigma sensitivity for NH & IH

If present error in θ_{13} is reduced by half, a 100 kT-yr exposure is capable of delivering a 4 sigma determination of the hierarchy.

Results..........Octant



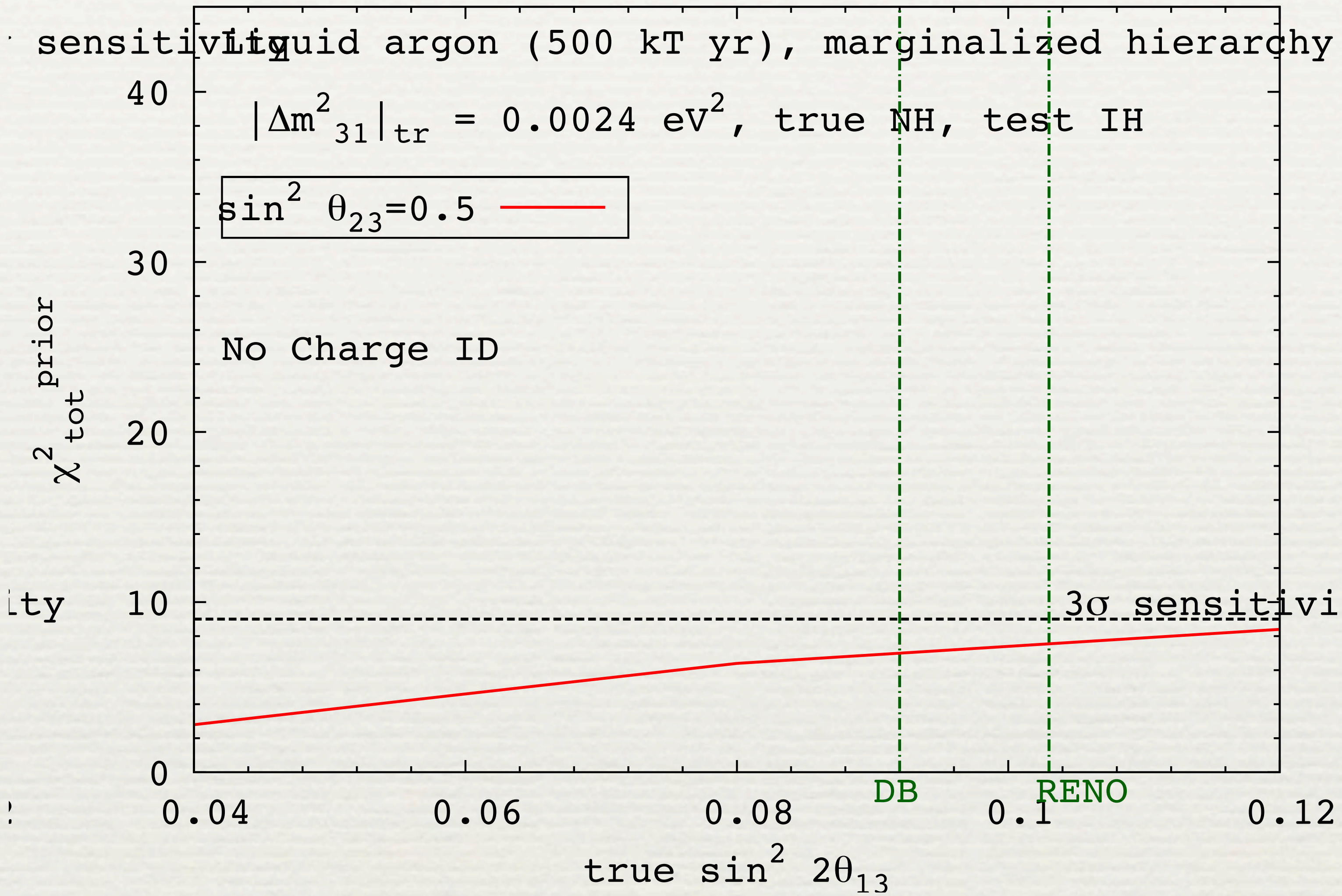


Present global best fit
Fogli et al arXiv 1205.5254

Octant sensitivity due to $\sin^4\theta_{23}$ term in survivial probability

>2 sigma determination for 500 kT-yr if $|\theta_{23} - \pi/4| > 3.5°$

Results....... Importance of charge id



3 sigma hierarchy determination with about 600 kT-yr exposure if no charge id.

Conclusions..........

Of three important goals in neutrino physics, two (hierarchy and octant) may be reachable significantly sooner than the third (CP).

A magnetized LAr-TpC, given its superior spatial, charge-id and calorimetric properties, can determine the hierarchy to 5 sigma with 250-kt-yr at current errors of θ_{13}

If this error is halved by future measurements, it can deliver a 4 sigma determination with 100 kT-yr exposure.

It can determine the octant to ~3 sigma with 500 kT-yr if θ_{23} at current global best fit value.

Conclusions..........

A 10-20 kT LAr-TPC with or without a magnetic field, sited underground to detect beam as well as atmospheric neutrinos would deliver even superior physics results. (work in progress.....)

Thank you for your attention!